

# Soil-Foundation-Structure Interaction Effects on Nonlinear Seismic Demand of Structures

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**ABSTRACT:** Investigating the seismic demand of structures integrating soil-foundation-structure interaction (SFSI) effects is a demanding task as a result of the complexity of the coupled dynamic problem. It is also augmented by the impact of uncertainty in the soil and structural parameters along with the randomness in earthquake characteristics. The objective of this research is to highlight SFSI effects on the seismic demand of nonlinear structures through a probabilistic methodology varying soil and structural parameters in a realistic combination and enforcing the adopted models to a range of earthquakes with different spectrum and type. Specifically, 1.36 million nonlinear time-history simulations are run over: (i) models consisting of a SDOF superstructure and a rheological soil-shallow foundation element; and (ii) their corresponding fixed-base models. The demand modification in structural distortion, drift and total displacement due to consideration of SFSI compared to the results of the corresponding fixed-base systems are quantified through a comprehensive statistical presentation. The results contradict prevailing views of the beneficial role of SFSI and show it does not hold in all cases. However, it does show that SFSI effects can be safely ignored with 50% confidence. The rigorous statistical Monte Carlo analysis presented is a significant first step towards reliability-based seismic design procedures incorporating foundation flexibility.

## 1 INTRODUCTION

Soil-foundation-structure interaction (SFSI) effect on seismic demand of structures is defined as a discrepancy in the structural response while considering flexible-foundation instead of ideal fixed-base assumption. Due to complexity of this coupled interaction phenomenon in addition to the combined impact of the uncertainty in soil and structural parameters and inherent randomness of the input ground motion, present treatment of seismic SFSI is not free of misconception. Modification in the seismic demand of elastic single-degree-of-freedom (SDOF) structures were firstly introduced by the extensive efforts of (Jennings and Bielak 1973), (Veletsos and Meek 1974) and (Veletsos and Nair 1975). They showed that the effect of inertial interaction can simply be expressed by a procedure in which the actual building is reduced to an equivalent SDOF system. This system consists of an increase in the fundamental natural period and a change in the associated modal damping of a fixed-base structure. They also recognized that SFSI consideration can either increase or decrease the seismic demand of the structures depending on the parameters of the system. Later, the presented replacement oscillator approach formed the basis of today's seismic design provisions (e.g., ATC-3-06 1984, FEMA 440 2005). Since in the design code, an idealized smooth design spectrum with a constant acceleration up to a certain period and a decreasing branch thereafter is used, it has been concluded that consideration of SFSI result in a decrease in structural seismic demand.

The response of the yielding structure-foundation systems has been examined by (Veletsos and Verbic 1974) and it was suggested that structural yielding decreases the effects of interaction since it increases the flexibility of the system. (Ciampoli and Pinto 1995) also have shown that the inelastic

seismic demand of a SDOF representation of structures essentially remains unaffected by SFSI and even showing a tendency to decrease. However, numerical results presented by (Bielak 1978) indicated that for non-linear hysteretic structures compliance of the foundation flexibility may lead to a larger displacement demand than what would be expected for a fixed-base system. Further confirmation was mentioned by (Miranda and Bertero 1994) based on analyses accomplished for motions recorded on soft soils. They demonstrated that in certain frequency ranges, period lengthening can result in an increase in the structural seismic demand. Recently, it is stated by (Avilés and Pérez-Rocha 2003) that the interaction effects for yielding systems is as important as those for elastic systems.

This controversy regarding the role of SFSI on the seismic demand of structures raises a question that whether finally SFSI is beneficial or detrimental (Mylonakis and Gazetas 2000) and even one step further, should it be considered in a daily design procedures or not. A rational way for achieving a rigorous evaluation of the SFSI effects on seismic demand of structures is to make use of a probabilistic approach. This methodology was utilized previously by the authors to quantify the SFSI effect on the response of elastic structures (Moghaddasi K. et al. 2009a) and yielding systems (Moghaddasi K. et al. 2009b). This paper aims at extending those results to investigate the modification in structural distortion, drift and total displacement seismic demand of SDOF systems with nonlinear behaviour and supported by an equivalent viscoelastic half-space.

In this paper, the associated variation on the considered seismic demands was investigated in a spectral format; the variation was demonstrated in terms of fundamental period of corresponding fixed-base (FB) superstructure. Following this quantification, the demand modification factors were scrutinized in terms of combined soil-structure key parameters at three levels of confidence: 50, 75 and 95%. Furthermore, for the 50% confidence level (mostly accepted design level), a curve was fitted to the corresponding data. Finally, the obtained demand modification curves were utilized to suggest a modification scheme to the current seismic design codes in order to incorporate the effect of SFSI.

## 2 STOCHASTIC SEISMIC DEMAND INVESTIGATION

While the analysis of a SDOF soil-foundation-structure (SFS) system is relatively straightforward, significant uncertainty in: (a) input ground motion spectrum and type and (b) parameters of the coupled SFS system can result in a wide range of structural seismic demand. This variation, although exists for an ideal fixed-base assumption, due to upper-bound consideration that is implicitly included in the spectral analysis (i.e., seismic design code procedure) mostly does not result in an un-conservative design. For the case of SFSI phenomenon, this variation can not be simply ignored.

To further explain this fact, Figure 1 illustrates the effect of aleatory (inherent randomness in input ground motion) and epistemic (randomness in the model parameters) uncertainty on the seismic strength demand of a flexible-base structure, as an example. Along with the strength response spectrum, the response of a FB system and its flexible-base counterpart is shown in this figure. Clearly, if a presumed structure with fundamental natural period of  $T_{FB}$  is supposed to two different earthquake ground motions, the strength demand ratio between FB and SFS system is different (Figure 1a). The demand for the SFS system can be either increased or reduced in respect to the original FB system, depending on the structural and earthquake characteristics and type. In contrast to this demonstration, it has been concluded from the current design code approach that any increase in the natural period of the structures due to SFSI effect may lead to a decrease in the strength demand of structures. As also shown in this figure, for an earthquake ground motion with a specific spectrum shape, depending on the relative configuration of structural parameters, foundation radius and soil characteristics, significant variation in the strength demand ratio is expected (Figure 1b). Once again, this variation can lead to either beneficial or detrimental role of SFSI.

Therefore, a rigorous investigation of any modification on the structural seismic demand due to SFSI requires: (i) considering all sources of uncertainty in the presumed analytical scenarios; (ii) computing the response of all randomly generated scenarios; (iii) presenting the results in a comprehensive statistical demonstration.

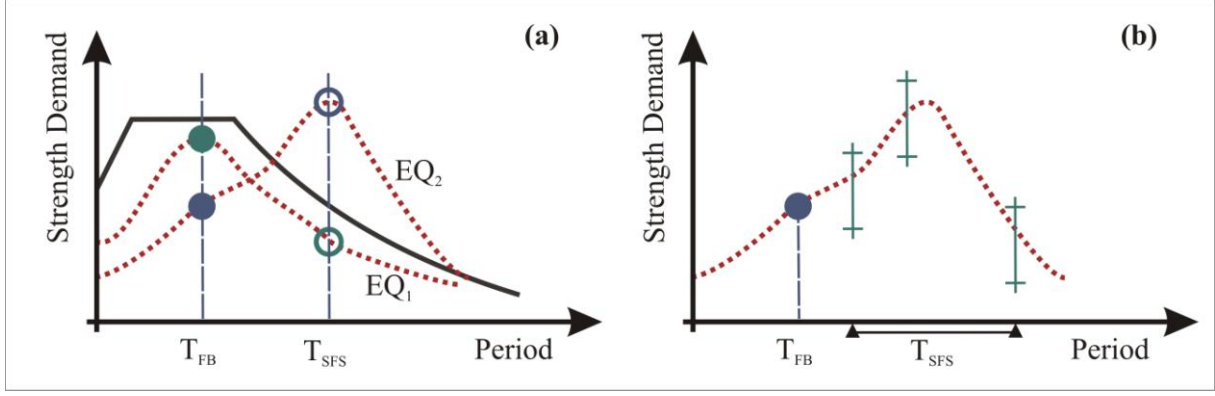


Figure 1. The effect of (a) aleatory and (b) epistemic uncertainty on the seismic demand of SFS systems

### 3 METHODOLOGY AND MONTE CARLO SIMULATION

An established rheological soil-shallow foundation-structure model (Sec. 3.1.1) was considered for this comprehensive probabilistic analysis. Its parameters were systematically defined randomly through a Monte Carlo simulation (Sec. 3.1.2) by carefully ensuring to satisfy the requirements of realistic models. The generated SFS models along with their FB counterparts were then subjected to a suite of earthquake ground motions (Sec. 3.1.3) via conducting nonlinear time-history analyses (Sec. 3.1.4). An overview of the aforementioned steps is elaborated in following, while more detailed information can be found in (Moghaddasi K. et al. 2009a) and (Moghaddasi K. et al. 2009b).

#### 3.1.1 Dynamic soil-foundation-structure model

The interacting soil-structure system investigated in this study is illustrated in Figure 1. It consists of a SDOF yielding superstructure supported by a rigid circular shallow foundation located on an equivalent linear viscoelastic soil stratum. The SDOF superstructure is an approximate representation of a FB multi-story building vibrating in its fundamental natural mode. This structure is characterized by height ( $h_{eff}$ ), mass ( $m_{str}$ ), lateral stiffness ( $k_{str}$ ) and damping ( $c_{str}$ ). To represent the nonlinear behaviour of the structure, a force-deflection relationship of the Takeda type (elastoplastic with strain hardening and stiffness degradation with increasing cyclic deformation amplitude) was considered. Damping was also assumed to be of the viscous type by a given 5% damping ratio with respect to the critical.

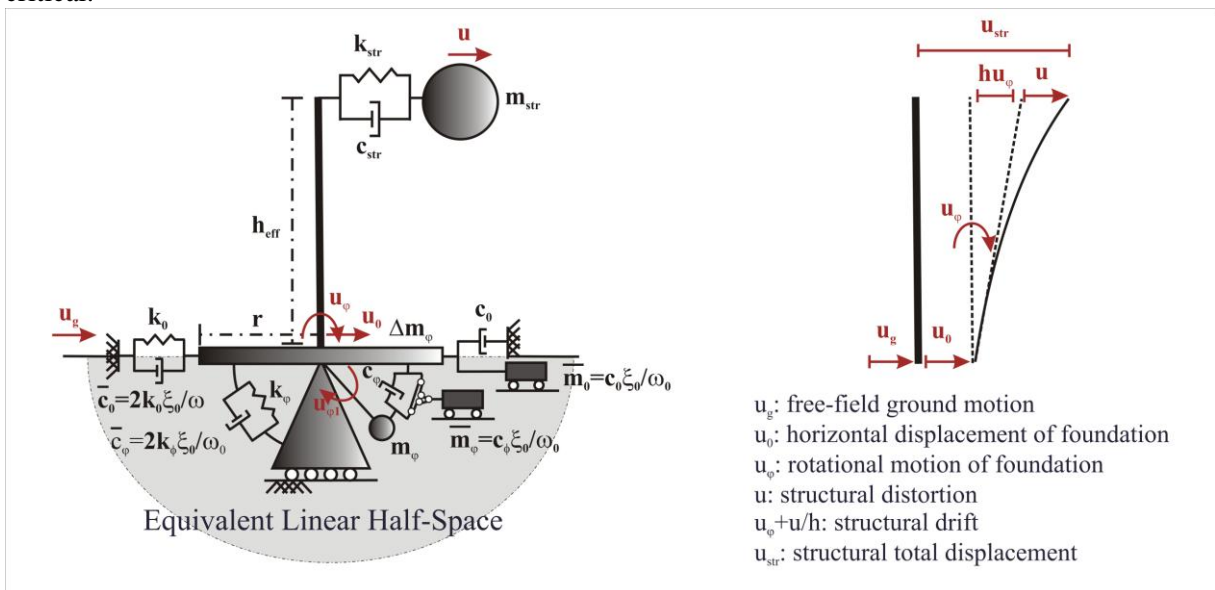


Figure 2. Dynamic soil-shallow foundation-structure model for horizontal and rocking foundation motions

The soil-foundation element was considered as a discrete model representing a rigid and perfectly bonded to soil circular footing that is resting on the soil surface. Moreover, the foundation was assumed to have no mass and mass moment of inertia along the horizontal axis. For evaluating the soil dynamic impedances incorporating soil nonlinearity, the frequency-independent coefficients of the developed rheological Cone model (Wolf 1994) was modified based on conventional equivalent linear method (Seed and Idriss 1970). In this model, the soil stratum is assumed to be a viscoelastic half-space. The parameters needed to quantify the dynamic impedances for considered horizontal (index 0) and rocking components (index  $\phi$ ) are presented in Table 1.

Table 1. Parameters of soil-foundation element based on the Cone model concept

Motion		Stiffness	Viscous damping	Added mass
Horizontal		$k_0 = \frac{8Gr}{2 - \nu}$	$c_0 = \rho V_s A$	-
Rocking	$\nu \leq 1/3$	$k_\phi = \frac{8Gr^3}{3(1 - \nu)}$	$c_\phi = \rho V_p I_r$	-
	$1/3 \leq \nu \leq 1/2$		$c_\phi = \rho(2V_s)I_r$	$\Delta m_\phi = 1.2(\nu - 1/3)\rho I_r r$
	Internal mass moment of inertia			
	$\nu \leq 1/3$	$m_\phi = \frac{9\pi}{32} \rho I_r r(1 - \nu)(\frac{V_p}{V_s})^2$		
	$1/3 \leq \nu \leq 1/2$	$m_\phi = \frac{9\pi}{8} \rho I_r r(1 - \nu)$		
Material damping		Additional parallel connected element (i=0 or $\phi$ )		
		Viscous damping to stiffness $k_i$		Inertial mass to damping $c_i$
		$\bar{c}_i = 2k_i(\xi_0/\omega_0)$		$\bar{m}_i = c_i(\xi_0/\omega_0)$

The parameters utilised in this table are defined as:

- $r$ ,  $A$  and  $I_r$ : Equivalent radius of the foundation, area of the foundation ( $A=\pi r^2$ ) and mass moment of inertia for rocking motion ( $I_r=\pi r^4/4$ ).
- $\rho$ ,  $\nu$ ,  $V_s$ ,  $V_p$  and  $G$ : Soil mass density, Poisson's ratio, soil shear wave velocity, soil longitudinal wave velocity and soil shear modulus.
- $\xi_0$  and  $\omega_0$ : Equivalent soil material damping and effective frequency of SFS system.

### 3.1.2 Realistic randomly generated soil-foundation-structure models

To investigate the SFSI effect on the structural seismic demand in the format of spectral analysis (objective of this study), a systematic scheme was utilized to generate the random models. A period range of 0.2, 0.3 ... 1.8 sec was selected to: (i) represent the fixed-base superstructures with total height of 3-30 m and (ii) satisfy the period-height relationship introduced in New Zealand Standard (NZS1170.5 2004). In order to cover the variability of model parameters at each considered fixed-base period ( $T_{FB}$ ), 1000 system configurations representing random but still realistic structural and soil conditions with the same  $T_{FB}$  were considered. The number 1000 was chosen with the intention to: (i) give the best fit uniform distribution for the randomly selected parameters and (ii) increase the accuracy of the Monte-Carlo simulation compared to the exact expected solution (Fishman 1996).

### 3.1.3 Seismic input

A suite of 40 ground motions (i) recorded on stiff/soft soil (specifically, type C and D based on USGS classification) and (ii) scaled to have reasonably distributed PGAs within the range of 0.3-0.8g was used as an input for the adopted time-history simulations. The number 40 was chosen to obtain an estimate of median response within a factor  $\pm 0.1$  with 95% confidence (Shome et al. 1998).

### 3.1.4 Nonlinear time-history analysis

The Newmark constant average acceleration scheme was used to integrate the equations of motion in nonlinear time-history analysis using a FEM code (Carr 2009).

## 4 RESULTS AND DISCUSSION

Maximum values for three aspects of structural seismic demand were examined in this study: (i) structural distortion ( $u$ ), (ii) structural drift ( $dr$ ) and (iii) structural total displacement. Structural distortion is the horizontal displacement of the superstructure relative to the foundation and represents the transmitted displacement/force to the superstructure. It also stands for the displacement ductility demand of the structure, since ductility is the ratio between the maximum experienced displacement and the yield displacement that is constant for a certain system. Structural drift is defined as the summation of drift value induced by structural distortion and structural lateral displacement due to rotational motion of foundation; the large values of this displacement can cause second-order effects (P- $\Delta$  effects). As a representative of top floor displacement, structural total displacement includes structural distortion, structural lateral displacement due to rotational motion of foundation and horizontal displacement of foundation.  $u/\mu$  and  $dr$  are two parameters that need to be considered for design of the structural elements, while  $u_{str}$  is the parameter that needs to be controlled to prevent pounding between adjacent buildings.

In order to simplify the presentation of the results from numerous time-history simulations, the maximum values resulted for SFS system were presented in a normalized format as a ratio with respect to the results obtained from corresponding FB system; the obtained ratio is called demand modification factor. Based on this type of presentation, SFSI is recognized to be detrimental in terms of a certain demand given that the demand modification factor is greater than unity.

The response quantities will be presented and discussed as functions of: (i) fundamental period of corresponding fixed-base superstructure ( $T_{FB}$ ), (ii) structural aspect ratio ( $h/r$ ), (iii) structural-to-soil stiffness ratio ( $\omega_{str}h/V_s$ ) and (iv) SFS-to-FB period ratio ( $T_{SFS}/T_{FB}$ ). To represent the existing variation in the demand modification factor in terms of  $T_{FB}$ , a box and whisker plot format is utilized. In this plot, the box has lines at 25<sup>th</sup> percentile (bottom line), median (middle line), and 75<sup>th</sup> percentile (top line) values. Whiskers extend from each end of the box to the 5<sup>th</sup> percentile and 95<sup>th</sup> percentile respectively. Outliers are the data with values beyond those indicated by the whiskers. The effect of  $h/r$ ,  $\omega_{str}h/V_s$  and  $T_{SFS}/T_{FB}$  on the demand modification factors is characterized through 50<sup>th</sup>, 75<sup>th</sup> and 95<sup>th</sup> percentile boundary lines representing different levels of confidence. Also, to provide a closed-form formula for the 50% confidence level (mostly accepted design level) a curve is fitted to the corresponding data.

### 4.1.1 The effect of SFSI on structural distortion demand

The effect of foundation flexibility on structural distortion demand is illustrated in Figure 3. Clearly, the demand modification factor ( $u_{SFS}/u_{FB}$ ) for 5<sup>th</sup>-95<sup>th</sup> percentile of the examined cases varies within the range of 0.3-1.2 depending on the fixed-base period (Figure 3 top-left). For more than 50% of the cases,  $u_{SFS}/u_{FB}$  is less than unity. However, it increases while considering higher level of confidence (75<sup>th</sup> and 95<sup>th</sup> percentile), but still the increase level is limited to 10% for most of the cases. Therefore, with 50% of confidence, SFSI effect on structural distortion does not appear really significant.

The demand modification factor for structural distortion is also demonstrated in terms of  $h/r$  (Figure 3 top-right),  $\omega_{str}h/V_s$  (Figure 3 bottom-left) and  $T_{SFS}/T_{FB}$  (Figure 3 bottom-right). The variation in the ratio of  $u_{SFS}/u_{FB}$  is presented for three levels of confidence: 50, 75 and 95%. In addition, a regression line is assigned to the data corresponding to the confidence level of 50%, which is the mostly desired level for the design purpose. When 50% is considered as the expected confidence level, the increase in  $h/r$  slightly reduces the ratio of  $u_{SFS}/u_{FB}$ , while due to increase of either  $\omega_{str}h/V_s$  or  $T_{SFS}/T_{FB}$ , a significant reduction is expected. Based on these results, it is concluded that the effect of  $h/r$  on the structural distortion demand modification factor is negligible. Furthermore, the SFSI appears to be beneficial when the ratio of  $\omega_{str}h/V_s$  or  $T_{SFS}/T_{FB}$  increases. The similar trend is observed for higher levels of confidence, except for some ranges the detrimental SFSI effect needs to be accounted for.

### 4.1.2 The effect of SFSI on structural drift demand

Figure 4 shows the effect of foundation flexibility on structural drift demand. As mentioned earlier, it includes the effect of rotational rigid body motion of the foundation on the system displacement.

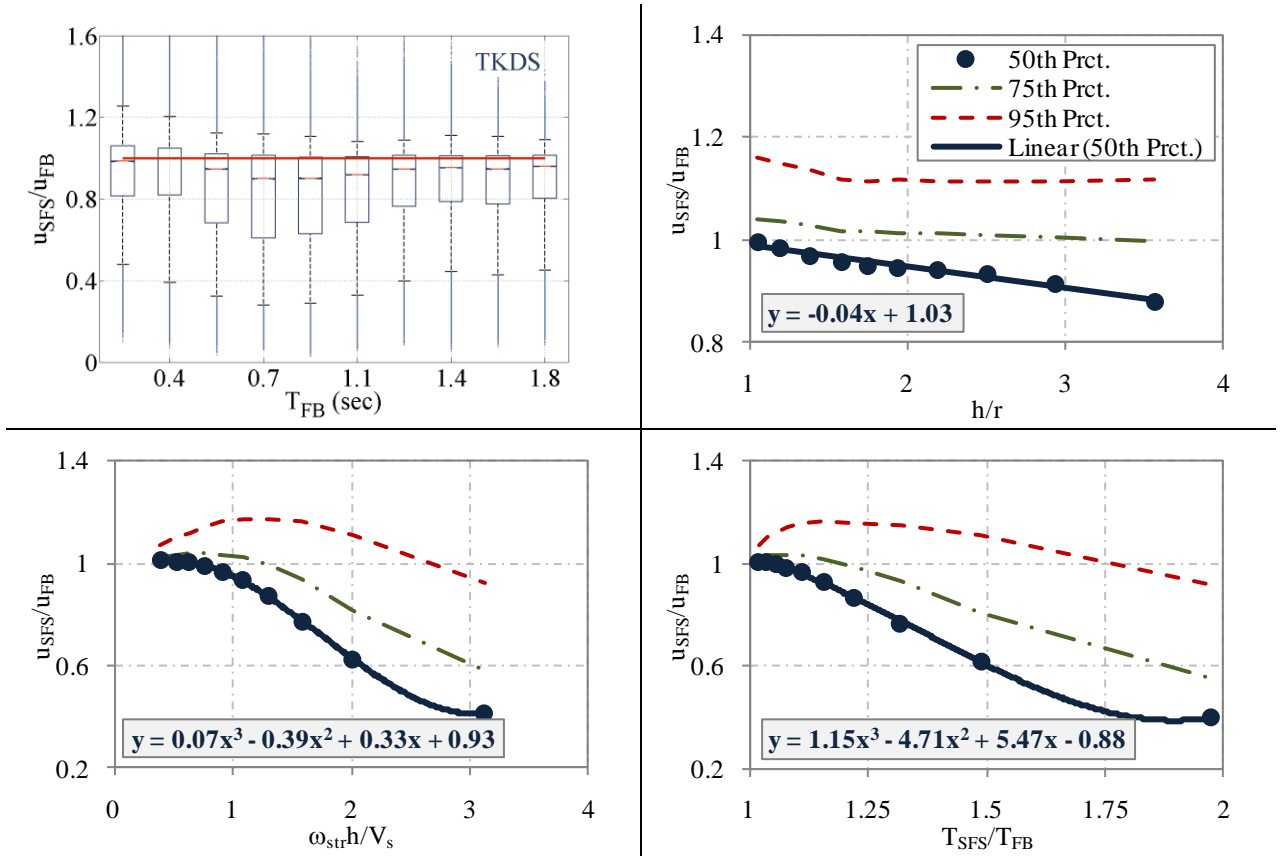


Figure 3. The effect of SFSI on structural distortion demand

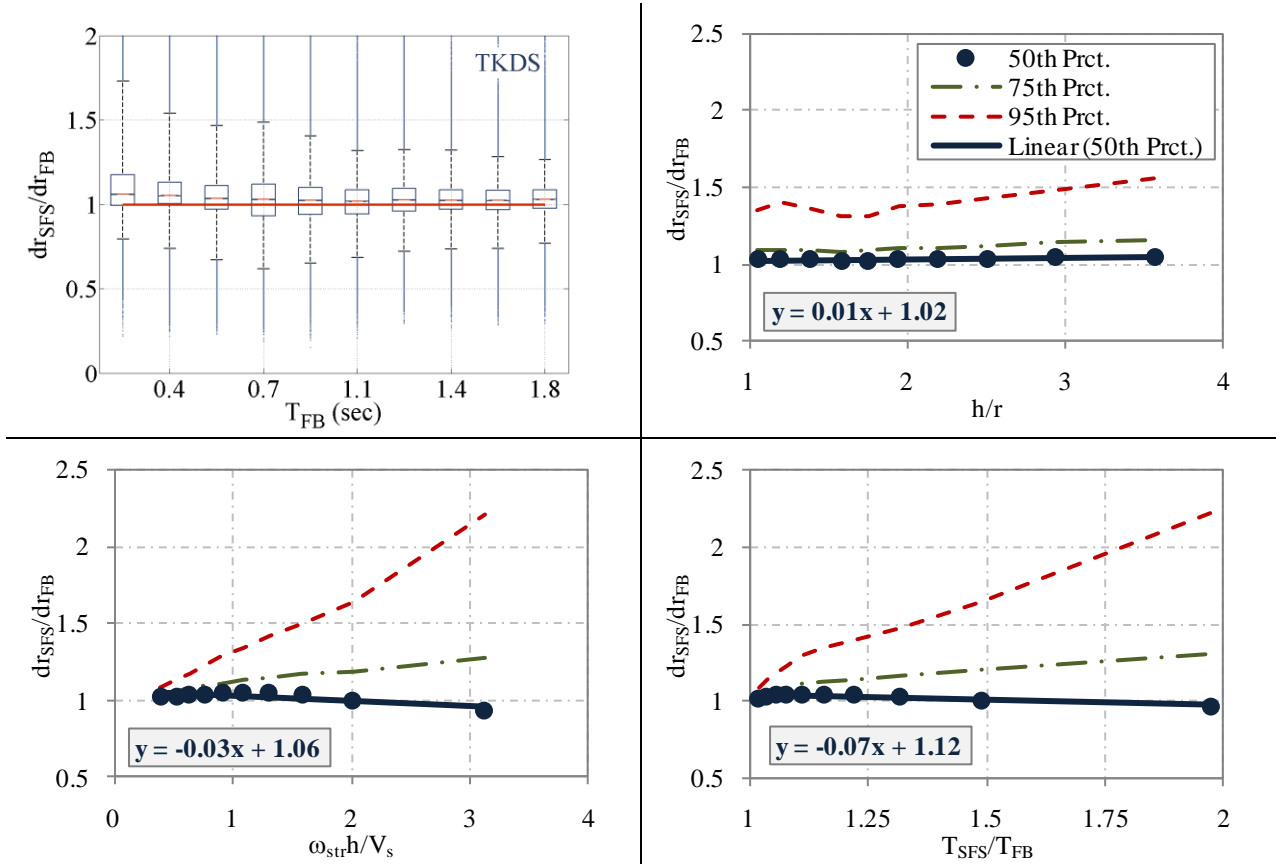


Figure 4. The effect of SFSI on structural drift demand

The drift demand modification factor ( $dr_{SFS}/dr_{FB}$ ) for 5<sup>th</sup>-95<sup>th</sup> percentile of the examined cases varies within the range of 0.6-1.7 depending on the fixed-base period (Figure 4 top-left). Clearly, for more than 50% of the cases,  $dr_{SFS}/dr_{FB}$  is greater than unity; nevertheless the increase level is not significant. It should be noted that, the demand modification factor increases while considering higher levels of confidence (75<sup>th</sup> and 95<sup>th</sup> percentile) and this time the increase level could be significant. Therefore, depending on the importance of the structure and the acceptable level of risk, the effect of SFSI on structural drift may be ignored or not.

Figure 4 also shows the demand modification factor for structural drift as a function of  $h/r$  (Figure 4 top-right),  $\omega_{str}h/V_s$  (Figure 4 bottom-left) and  $T_{SFS}/T_{FB}$  (Figure 4 bottom-right). The nearly horizontal trend of the regression line at 50<sup>th</sup> percentile shows that  $dr$  is only weekly sensitive to all of three variables. Furthermore, the constant value of the regression line that is almost unity leads to the idea that adding flexibility to the foundation almost does not change the demand of structural drift. However, when higher levels of confidence are considered different interpretation shows up. For an increase in any of the three selected parameters that regulate SFSI phenomenon, the demand modification factor tends to increase; and the observed raising trend is more noticeable for higher level of confidence. This fact confirms that for design of systems with high level of importance, consideration of SFSI may result in higher drift levels that will cause second-order effect (P- $\Delta$  effect).

#### 4.1.3 The effect of SFSI on structural total displacement demand

When the effect of both rigid motions, that caused by foundation flexibility, on the structural displacement response is accounted, Figure 5 shows the demand modification factor,  $(u_{str})_{SFS}/(u_{str})_{FB}$ . The observed trend in this case is almost similar to what is explained for drift demand, except that the variation of  $(u_{str})_{SFS}/(u_{str})_{FB}$  for 5<sup>th</sup>-95<sup>th</sup> percentile of the examined cases is slightly higher and placed in the range of 0.7-2. The slightly increase is not unexpected since one additional rigid body motion is included. Following this fact, when pounding effect needs to be accounted for, SFSI should be considered in the analysis of structures with high level of importance.

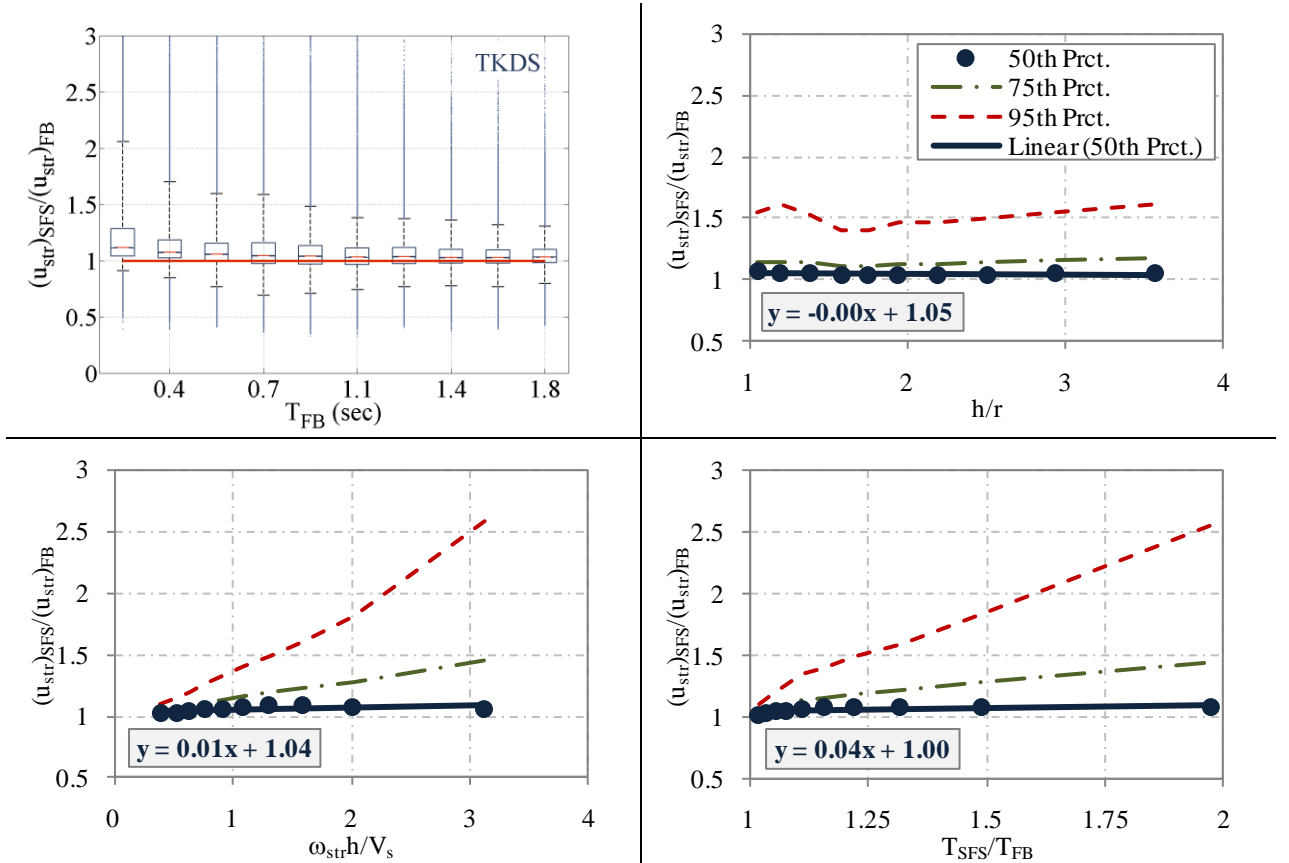


Figure 5. The effect of SFSI on structural total displacement demand

## 5 PROPOSAL FOR DESIGN PROCEDURES

On the basis of this robust statistical study, a modification to the current seismic design procedures is suggested in order to incorporate SFSI effects. First, the designer or the owner should decide on the desired level of confidence. If a design with 50% of confidence (most commonly accepted level) is required, then SFSI effect on structural response can be neglected. On the other hand, if a higher confidence level needs to be considered, depending on the design parameter and the certain situation of structure and the soil, the seismic demand obtained for a FB system can simply be modified by a factor to incorporate SFSI effect.

The SFS-to-FB period ratio ( $T_{SFS}/T_{FB}$ ) is a variable mostly combines the structural and soil parameters into a unified one. Therefore, it is selected as the variable should be used to define the demand modification factors. While the ratio of  $T_{SFS}/T_{FB}$  is known for a certain structure and soil scenario, the modification factor for any of the three introduced structural seismic demand can be extracted from the graphs presented through Figures 3-5 (bottom-right), respecting the confidence levels of 75 and 95%. This modification factor is then used as a multiplier to present the expected change in seismic demand of a FB system due to SFSI consideration.

## 6 CONCLUSION

A comprehensive Monte Carlo simulation was undertaken with the purpose to quantify the effects of SFSI on the seismic demand of structures. Consideration of a large number of models incorporating wide range of soil, foundation and structural parameters subjected to a suite of earthquake ground motions with different spectrum allowed to cover the most common soil-structure-earthquake scenarios. The results indicate that:

- Although SFSI can increase structural distortion seismic demand, this effect is not very significant and, further, the effects can be neglected with 50% level of confidence. The variation of seismic demand in terms of structural distortion is independent of  $h/r$  ratio, nevertheless, is influenced by  $\omega_{str}h/V_s$  and  $T_{SFS}/T_{FB}$  ratios significantly. An increase in the value of  $\omega_{str}h/V_s$  and  $T_{SFS}/T_{FB}$  ratios corresponds to a reduction in the demand modification factor that leads to the scenarios with the more beneficial SFSI effects.
- In most cases SFSI produce an increase in the structural drift and maximum displacement demand. The increase level is not very significant for 50% level of confidence; however, cannot be neglected for higher levels of confidence. This increase is only results from the rigid body components arising from the foundation motion, and is not because of the greater inelastic demand of structure. The increase level rises up due to an increase in the ratio of  $h/r$ ,  $\omega_{str}h/V_s$  and  $T_{SFS}/T_{FB}$  with sharper trend for higher levels of confidence.
- For higher levels of confidence, a demand modification factor can be introduced based on SFS-to-FB period ratio ( $T_{SFS}/T_{FB}$ ) to adjust the response of a FB system for SFSI incorporation.

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